Apr 1st, 8:00 AM

An Overview of Structures and Materials for Future Space Vehicles

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AN OVERVIEW OF STRUCTURES AND MATERIALS FOR FUTURE SPACE VEHICLES

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PRESENTED AT

TWENTY-THIRD SPACE CONGRESS

COCOA BEACH, FLORIDA

APRIL 22-25, 1986

ABSTRACT

The NASA, primarily at Langley Research Center, has been conducting analytical and experimental developmental programs for high temperature structures for over 30 years. Over this time many significant technologies in both structures and materials have evolved. The structures and materials for primary airframe concepts such as metal-matrix composites, organic composites, advanced metals and carbon-carbon have emerged from laboratory curiousities to state-of-the-art structures. New manufacturing processes, such as electron beam welding, superplastic forming and diffusion bonding, allow innovative design concepts that were impracticable only a decade ago. Several of these technologies have been flight demonstrated as secondary structures such as flaps, rudders and speed brakes. Analytical techniques have improved to the point where the design and analysis of complex thermostructural concepts can be readily evaluated in relatively short time frames, when only 20 years ago these techniques were unknown. This paper reviews these technologies, proven, emerging and conceptual with emphasis on their applications to space vehicles.

Expert Systems as Applied to Future Space Transportation Systems

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MARCH 18, 1986

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EXPERT SYSTEMS

Expert systems are computer hardware and software systems, which are used to solve real world practical problems through the use of heuristics that are encoded in its knowledge rule base. Expert systems differ from human experts in that when the available heuristics fail to handle a situation, the human expert can call upon deep knowledge (principles) of the domain and effect a solution; the capabilities of a computer expert system are limited by the heuristics (knowledge) provided in its knowledge rule base.

Expert systems are generally most efficient when their knowledge rule base is in the range of several hundred rules i.e., no more than one thousand and cover a very narrow domain. This approach allows development and maintenance of the system to be manageable, i.e., the development task is not overwhelming and can be managed by a small team of systems and knowledge engineers. As a general rule, an expert system should include the expertise derived from several experts in the target domain in order to eliminate inconsistencies associated with normal human behavior.

Expert Systems

DEFINITION: A SYSTEM CONSISTING OF THE HARDWARE & SOFTWARE TO SOLVE A REAL WORLD PROBLEM AT AN EXPERT LEVEL, A SUBSET OF KNOWLEDGE BASED SYSTEMS

CHARACTERISTICS:

1. HEAVILY DEPENDENT ON ENCODED KNOWLEDGE
2. KNOWLEDGE BASE SEPARATE FROM PROGRAM CONTROL
3. USUALLY IMPLEMENTED AS A RULE BASED "IF-THEN" SYSTEM
4. SOLVES PROBLEMS IN A NARROW DOMAIN
5. SHOULD INCLUDE EXPERTISE FROM SEVERAL EXPERTS; ELIMINATES INCONSISTENCIES ASSOCIATED WITH HUMAN BEHAVIOR

WHY USE AN EXPERT SYSTEM

Usage of expert systems to perform tasks formerly assigned to humans usually provides the benefits realized from computer automation of any task, i.e., a reduction in the number of persons required to perform the task and reduction in opportunity for the introduction of human error into the task process, which formerly introduced inconsistency of output.

In addition, an expert system approach to a problem often provides realizability where failure was previously encountered due to the cyclic nature of procedural programs as compared to the pattern matching paradigms used in most ES shells.

Another apparent attractive feature of expert systems, which use a rule-based "IF - THEN" approach for mechanization, is the relative ease of software maintenance as compared to traditional software approaches wherein intermodular dependence causes software changes to propagate throughout the software system modules.

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Why Use an Expert System (ES)

- AN ES PROVIDES ALL THE USUAL BENEFITS ASSOCIATED WITH AUTOMATION OF A TASK
    - REDUCTION IN NUMBER OF REQUIRED PERSONNEL
    - IMPROVED EFFICIENCY
    - RESULTS ARE CONSISTENT
    - REDUCES TIME USED ON REPETITIVE, MUNDANE TASKS
- ES APPROACHES TO PROBLEMS SOMETIMES PROVIDE SOLUTIONS WHEN CONVENTIONAL/PROCEDURAL SOFTWARE APPROACHES FAIL
    - XCON (R1), THE DEC COMPUTER SYSTEM DESIGN EXPERT FAILED TWICE USING PROCEDURAL LANGUAGES BEFORE OPS5 WAS USED WITH AN ES APPROACH
    - PATTERN MATCHING ES PARADIGMS CIRCUMVENT THE FUTILITY OF COMBINATORIAL EXPLOSION THAT SOMETIMES RESULTS FROM THE USE OF PROCEDURAL LANGUAGES
- RULE BASED SYSTEMS ARE GENERALLY EASIER TO MAINTAIN THAN SOFTWARE SYSTEMS USING PROCEDURAL LANGUAGES
- RULE BASED SYSTEMS PROMOTE RAPID PROTOTYPING & ITERATIVE REFINEMENT

MAJOR EXPERT SYSTEM TOOLS

The OPS languages form the most popular collection of expert system building tools. These languages are so-called forward chainers. These tools follow the paradigm found in OPS-5, originally developed at Carnegie Mellon University. OPS-83 is the most advanced tool in this family. It allows the user greater flexibility in application design because it is a more general tool than OPS-5. OPS-83 runs on IBM PCs and runs very efficiently on the DEC VAX series. OPS-83 can call modules written in other languages available on the system.

ART and KEE are expert system development environments. These systems have facilities to allow commercial development of large expert systems. These facilities include: a very general pattern matching and rule language which supports many user development needs and the capability to perform both forward and backward chaining, a hierarchical inheritance mechanism for the representation of declarative knowledge, a mechanism which allows hypothetical reasoning and time based modeling and an easy to use graphics interface development environment. KEE and ART have some differences, ART is a more general tool and KEE supports object oriented programming, but both tools are essentially equivalent. These tools are available for the more popular Lisp machines; ART is available on the DEC VAX series as well.

Prolog is a logic programming language. Prolog has mainly been used for theorem proving type applications, but can be used for more general applications. The knowledge representation used in Prolog is different from that used in the other tools mentioned. Also, the rule format is somewhat different. The inner mechanism of Prolog uses an approach different from either forward or backward chaining. It uses a powerful inferencing mechanism called resolution. Many Prolog implementations are available.

Major Expert System (ES) Tools

- "OPS" LANGUAGES — A FORWARD CHAINING ES TOOL
  - OPS5 BASED ON FRANZ LISP
  - OPS5 BASED ON BLISS 32
  - OPS83 BASED ON THE "C" LANGUAGE
- AUTOMATED REASONING TOOL (ART)
  - A ROBUST TOOL THAT PROVIDES INHERITANCE, DATA STRUCTURES (SCHEMATA), A POWERFUL RULE LANGUAGE & VIEW POINTS, WHICH ALLOW HYPOTHETICAL REASONING AND/OR TIME BASED MODELING
- KNOWLEDGE ENGINEERING ENVIRONMENT (KEE)
  - VERY SIMILAR TO ART
- PROLOG
  - LOGIC PROGRAMMING
  - DECLARATIVE APPROACH

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EXPERT SYSTEM (ES) TECHNOLOGY CONCERNS AND ISSUES

Expert system (ES) technology is a relatively immature technology and is only at the threshold of usage for commercial, industrial and aerospace applications. This immaturity of technology and applications experience manifests itself in a general lack of sophisticated tools for efficient development of expert system applications products, and sometimes a reluctance to commit resources to usage of the technology. Contemporary ES shells and environments are in a period of intense development effort, sparked by fierce competition in pursuit of a lucrative market.

This immaturity and continual development effort manifests itself further in products that in some cases are far from optimized, but which are being constantly improved in pursuit of the ultimate product. Thus, standards are presently lacking in the technology; standards similar to MIL-STD 2167, which defines the total life cycle requirements for traditional software projects, including integration, validation and verification details.

Although the present intense development activity generally tends to introduce some instability into the technology in its present phase of development, it is clear that the continued intense participation by these same elements, i.e., government, academia and industry, will serve to provide the necessary tools to promote efficient application of the technology to future space transportation system elements.

Expert System (ES) Technology Concerns and Issues

- THERE ARE NO ES STANDARDS OR SPECIFICATIONS SIMILAR TO MIL STD 2167

- NO SPACE QUALIFIED HARDWARE IS AVAILABLE

- CONTEMPORARY ES TOOLS ARE IMMATURE, SOMETIMES INEFFICIENT & SOME ARE COMPUTER RESOURCE HOGS, i.e., CPU & MEMORY REQUIREMENTS. INTENSIVE INDUSTRY DEVELOPMENT OF TOOLS RESULTS IN PRODUCTS THAT ARE CONSTANTLY CHANGING (EVOLUTION)

- NO STANDARDS EXIST FOR VALIDATION & VERIFICATION TASKS
    - CAN COMPARE RESULTS TO SOLUTIONS PROVIDED BY HUMAN EXPERTS
    - OTHER TEST CRITERIA NEED TO BE DEFINED

- RELUCTANCE TO RELINQUISH RESPONSIBILITY TO A COMPUTER SYSTEM

- KNOWLEDGE ACQUISITION PROCESS IS NOT WELL UNDERSTOOD

☆ **BUT INTENSE ACTIVITY IS ON-GOING IN ACADEMIA, GOVERNMENT & INDUSTRY TO ALLEVIATE THESE CONCERNS**

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EXPERT SYSTEM COST DRIVERS

The complexity of the problem is a major cost driver for any type of automation. Artificial Intelligence and expert system techniques are used to automate functions which are inherently difficult and seem to require human reasoning or expertise. Problems can be solved today using these new techniques which would not even have been attempted via automation just a few years ago.

It is well known that the extraction of information from experts can be very time consuming and inefficient. Of course, if the experts are not readily available or if high demand (rare) skills are inherent to the target domain the cost of the knowledge acquisition process may be relatively high. Also, if the problem to be solved has some experts but no one understands the complete solution or the solution knowledge is hard to represent then the cost for an expert system will increase.

Another important cost driver is availability of expert system development tools. These tools can speed development and lower maintenance costs. Tools to assist the knowledge engineer in the knowledge acquisition task are almost non-existent today. These tools would decrease up-front costs and help in the decision to automate, using expert systems, by disclosing the availability of useful information early in the design phase. Standards for design, development and maintenance of expert systems will decrease costs by streamlining the processes and contributing to greater information sharing between various developers.

Expert System Cost Drivers

- COMPLEXITY OF THE PROBLEM
  - KEW BATTLE MANAGEMENT — EXTREMELY COMPLEX
  - EXCABL THE SHUTTLE-ORBITER PAYLOAD BAY CABLING EXPERT IS SIGNIFICANTLY LESS COMPLEX
- AVAILABILITY & QUALITY OF EXPERTS
- QUALITY & AVAILABILITY OF DEVELOPMENT TOOLS
  - ES SHELLS
  - AUTO RULE GENERATORS
  - LACK OF STANDARDS

POTENTIAL EXPERT SYSTEM APPLICATIONS TO FUTURE SPACE TRANSPORTATION SYSTEM ELEMENTS

Numerous opportunities exist for the application of expert systems technology to space transportation system tasks to realize benefits through reduction in requirements for support personnel, improved efficiency and reduction in the opportunities for introduction of human error into the process. In the category of operations related to ground and orbital platform installations, the following are presented as typical application opportunities:

Automated Launch Control - the system functions to manage the launch countdown process.

Vehicle Processing Planner - serves to provide the planning function for vehicle processing and launch preparatory activities as the vehicle moves through the various launch site processing facilities.

Automated Support Equipment Checkout - automatic performance of certification or validation testing of facility equipment.

Automated Malfunction Diagnosis and Safing - performs the monitor, diagnosis and safing function for the target system. Can be interfaced to the vehicle processing planner to assist in the logistics and human resources aspects of the planning function.

Maintenance Advisor - replaces paper manuals and provides interactive assistance to the maintenance performer.

Automated Launch Vehicle Checkout - performs automatic testing of the launch vehicle systems.

System Schematic Manager - provides a computer based schematic system, which provides current data regarding the vehicle and support facility designs.

Payload Processing Advisor - provides details regarding the handling, repair and maintenance of specific payloads.

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Potential Expert System Applications to Future Space Transportation System Elements

- GROUND FACILITIES & ORBITAL PLATFORMS
    - AUTOMATED LAUNCH CONTROL
    - VEHICLE PROCESSING PLANNER
    - AUTOMATED SUPPORT EQUIPMENT CHECKOUT
    - AUTOMATED MALFUNCTION DIAGNOSIS & SAFING
    - MAINTENANCE ADVISOR
    - AUTOMATED LAUNCH VEHICLE CHECKOUT
    - SYSTEM SCHEMATIC MANAGER
    - PAYLOAD PROCESSING ADVISOR

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POTENTIAL EXPERT SYSTEM APPLICATIONS TO FUTURE SPACE TRANSPORTATION SYSTEM ELEMENTS

On-board (vehicle) expert systems may be used for the following applications:

Automated Self Checkout - provides performance testing of flight systems during ground or platform prelaunch processing.

Automated Malfunction Diagnosis and Safing (same as previously described for the ground and orbital platform opportunities).

Autonomous Mission Control - provides the mission control function for scheduling and execution of flight events, or may function in an advisory capacity for manned missions if desired.

The application of expert systems technology to the space transportation system configuration management and planning tasks is treated separately due to the enormity and complexity of the task, wherein all the resources, such as launch facilities, tracking facilities, launch vehicle inventories and production plans, satellite inventories and production plans, and satellite mission planning requirements, which constitute the national space transportation system, are managed to optimize the flight scheduling and flight manifest definitions.

SOFTWARE MAINTENANCE AND TESTING

Code Maintenance Advisor - provides automated check lists and coordination of maintenance activities.

Code Test Advisor - advises the programmer on those tests which must be performed following code modifications.

Automated Test Data Analysis - analyzes test data based on expert rules describing the expected results of a test run.

Potential Expert System Applications to Future Space Transportation Elements

- VEHICLE (ON-BOARD EXPERTS)
  - AUTOMATED SELF-CHECKOUT
  - AUTOMATED MALFUNCTION DIAGNOSIS & SAFING
  - AUTONOMOUS MISSION PLANNING
  - PAYLOAD PROCESSING ADVISOR
- SPACE TRANSPORTATION SYSTEM MANAGEMENT
  - FLIGHT SCHEDULING
  - FLIGHT MANIFEST MANAGEMENT
  - RESOURCE MANAGEMENT
- SOFTWARE MAINTENANCE & TESTING
  - CODE MAINTENANCE ADVISOR
  - CODE TEST ADVISOR
  - AUTOMATED TEST DATA ANALYSIS

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SUMMARY OF EXPERT SYSTEM TECHNOLOGY BENEFITS

The use of expert system (ES) technology sometimes permits automation of tasks in cases where automation attempts using procedural software languages failed. This feature is exemplified by XCON or R1, the Digital Equipment Corporation computer system configuration expert, which suffered two failed attempts at implementation using procedural software languages prior to the success realized with the OPS5 expert system shell. This feature stems from the pattern matching facilities of rule based expert systems in contrast to the cyclic execution nature of procedural languages.

Thus, expert systems applications provide the opportunity for improved efficiency in the target task, wherein productivity is increased on a basis of reduced time requirements, personnel are freed from the tedium of the performance of mundane tasks, consistency of task output is realized, and in the area of direct space vehicle launch operations, launch turn around time is reduced. Space programs can also benefit in the reduction of numbers of personnel required to support the various operations, reduction in the number of opportunities for introduction of human error into the task process and by retention of expertise in a particular domain or task that might otherwise be lost through personnel attrition.

Summary of ES Technology Benefits

- **AUTOMATION WHERE PREVIOUSLY EXPERIENCED FAILURE**
- **IMPROVED EFFICIENCY**
  - **REDUCED LAUNCH TURNAROUND TIME**
  - **CONSISTENT RESULTS**
  - **INCREASED PRODUCTIVITY**
- **REDUCTION IN SUPPORT PERSONNEL**
- **REDUCTION IN OPPORTUNITIES FOR HUMAN ERROR**
- **RETENTION OF EXPERTISE**

$ SAVINGS

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REPRESENTATIVE ROCKWELL INTERNATIONAL SPACE TRANSPORTATION SYSTEM DIVISION PROJECTS

Safing And Failure-detection Expert (SAFE) is a prototype which consists of a shell of domain independent Automated Reasoning Tool (ART) rules which perform monitoring, failure detection and diagnosis on the sensor-based system described by a set of user supplied ART domain rules describing the system's devices and device interactions. Work is in progress to add in a safing function and a user interface which will make it easy for a system engineer to create domain rules.

Shuttle orbiter payload bay cabling expert (EXCABL) provides the installation details required to connect orbiter services to payloads using a standard inventory of cables. The output is the wiring schematic used to perform the cable routing task.

Knowledge Acquisition Tool (KAT) is a tool to aid in the extraction and organization of information regarding the solution of a problem. A goal tree approach has been taken which lends itself to possible automatic rule generation.

Lightning Expert System (LES) acts as an advisor for performance of lightning effects analysis on orbiter systems.

Inertial measurement unit expert determines the acceptable duration of orbiter on-pad launch hold periods on the basis of performance data acquired from the IMU redundant set.

Abort region determinator issues abort mode calls to the orbiter crew on the basis of state vector data and propulsion systems status.

Fluid apparatus experiment expert is an early prototype of space-qualified expert system. Plans include the use of a compact Lisp machine. This expert will automate certain types of materials processing.

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Representative Rockwell International Space Transportation System Division Projects

PROJECT	STATUS
SAFING & FAILURE DETECTION EXPERT (SAFE)	PROTOTYPE COMPLETE
ORBITER PAYLOAD BAY CABLING EXPERT (EXCABL)	PROTOTYPE PHASING INTO PRODUCTION USAGE
KNOWLEDGE ACQUISITION TOOL (KAT)	PROTOTYPE EVALUATION
LIGHTNING EXPERT SYSTEM (LES)	PROTOTYPE IN DEVELOPMENT
INERTIAL MEASUREMENT UNIT EXPERT	REQUIREMENTS DEFINITION PHASE
ABORT REGION DETERMINATOR	REQUIREMENTS DEFINITION PHASE
FLUID EXPERIMENT APPARATUS	REQUIREMENTS DEFINITION PHASE

EXPERT SYSTEM ARCHITECTURE ISSUES

Expert systems are CPU intensive processes and therefore will perform much better if they could be broken up into separate processes running on separate processors. The algorithms which many inference engines use lend themselves well to a parallel architecture. Therefore parallel architectures hold great promise in the realization of practical expert systems. New parallel architecture hardware has recently been developed by several independent companies, however many problems still exist in the best way to program these machines.

Handing over the responsibility from experts to expert systems will require confidence in the reliability of these systems. Reliability can be enhanced with provisions for both hardware and software redundancy. Research is active in the field of large expert system architectures. These architectures hope to promote software redundancy, greater system performance and ease of system maintenance. The most promising of these architectures are the distributed expert system designs. In these architectures, independent agents solve the problems which fall under their domain of expertise. These agents may typically have expert bosses which assign their work or the processor on which they should complete their task. A system like this will have graceful degradation when processors or agents fail because other agents or groups of agents will cooperate to complete the failed agents important tasks even though they may not be expert enough to come up with the optimal solution.

Another architectural feature which must be dealt with is the interfacing of expert systems with procedural languages like Ada. Procedural languages are much more efficient at some tasks than expert systems. When this is the case, an expert system can hand-off a calculation to a procedural program and proceed with its problem solving.

Expert System Architecture Issues

- PARALLEL PROCESSING
- REDUNDANCY PROVISIONS
- DISTRIBUTED/HIERACHICAL/CENTRALIZED
- INTERFACE WITH PROCEDURAL LANGUAGES (Ada)

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SUMMARY AND CONCLUSIONS

Future space transportation system programs must utilize cost reduction tools and techniques in order to become viable entities in the prevailing political and economic environments. Expert system and knowledge based technology can provide this opportunity for significant cost savings. Current active programs may achieve some limited cost benefits via piecemeal applications to identifiable worthwhile targets. But, the real value of the technology lies in the inclusion of its principles in the initial requirements definition phase for the target program and application of these principles throughout the program life cycle. Therefore, it is clear that accommodation of this kind of usage which encompasses the application of technology using sound engineering principles requires the development of tools to accommodate implementation. This means that expert system life cycle standards similar to MIL-STD 2167 are required, various expert system architectures must be developed, e.g., distributed and hybrid distributed systems, large and complex expert systems must easily integrate and interface with procedural language systems such as Ada, and tools that automate the process of knowledge base rule generation from domain experts must be developed to simplify the knowledge acquisition process. Development of these tools and capabilities is realizable within the capabilities of existing technologies. In the current environment of intensive development effort in pursuit of these tools and capabilities, it is reasonable to assume expert system technology will be in a condition suitable to support development of the next generation of space transportation system elements.

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Summary and Conclusions

ADVANCED SPACE PROGRAMS MUST USE EXPERT SYSTEM TECHNOLOGY TO REDUCE PROGRAM COSTS

- ES TOOLS DEVELOPMENT MUST CONTINUE
- INDUSTRY STANDARDS ARE REQUIRED
- ES ARCHITECTURES REQUIRE DEVELOPMENT
- DEVELOPMENT OF KNOWLEDGE ENGINEERING RESOURCES